Vortex drag in a Thin-film Giaever transformer

Yue (Rick) Zou (Caltech)

Gil Refael (Caltech)

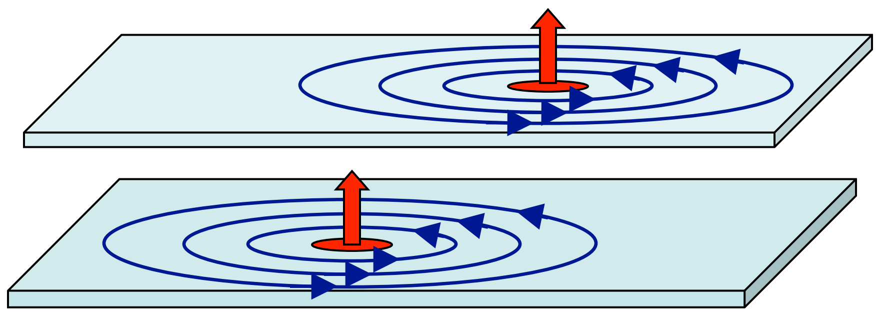
Jongsoo Yoon (UVA)

Past collaboration:

Victor Galitski (UMD)

Matthew Fisher (station Q)

T. Senthil (MIT)



Outline

- Experimental background – SC-metal-insulator in InO, TiN, Ta and MoGe.

- Two paradigms:
  - Vortex condensation: Vortex metal theory.
  - Percolation paradigm

- Thin film Giaever transformer – amorphous thin-film bilayer.

- Predictions for the no-tunneling regime of a thin-film bilayer

- Conclusions

Quantum vortex physics

SC-insulator transition

• Thin films: B tunes a SC-Insulator transition.

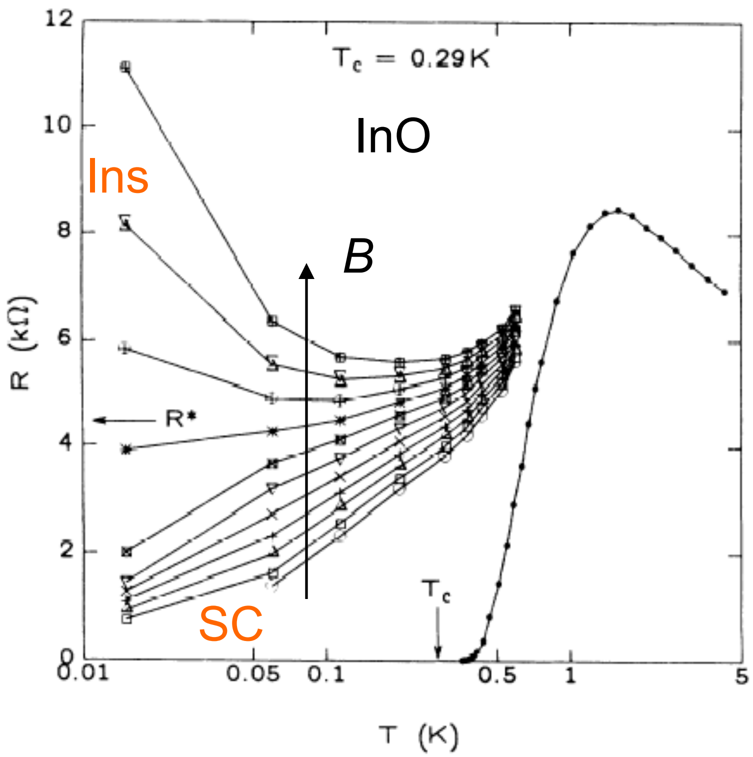
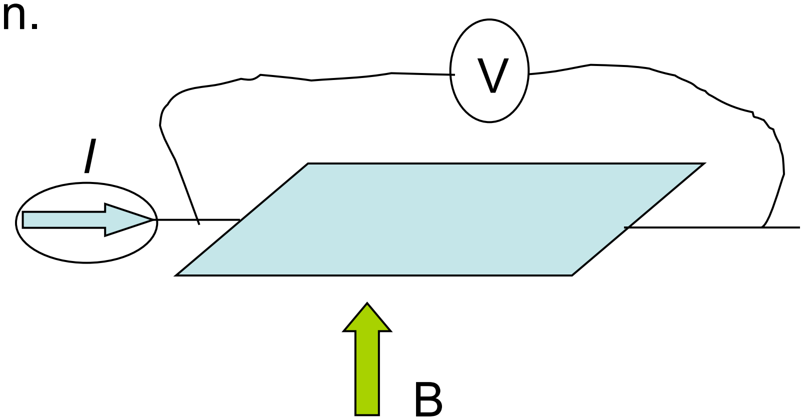


FIG. 1. Logarithmic plots of the resistance transitions in zero field (●) and nonzero field (open symbols) for a film with $T_c = 0.29$ K. The isomagnetic lines range from $B = 4$ kG (○) to $B = 6$ kG (□) in 0.2-kG steps. The horizontal and vertical arrows identify R^* and T_c, respectively.

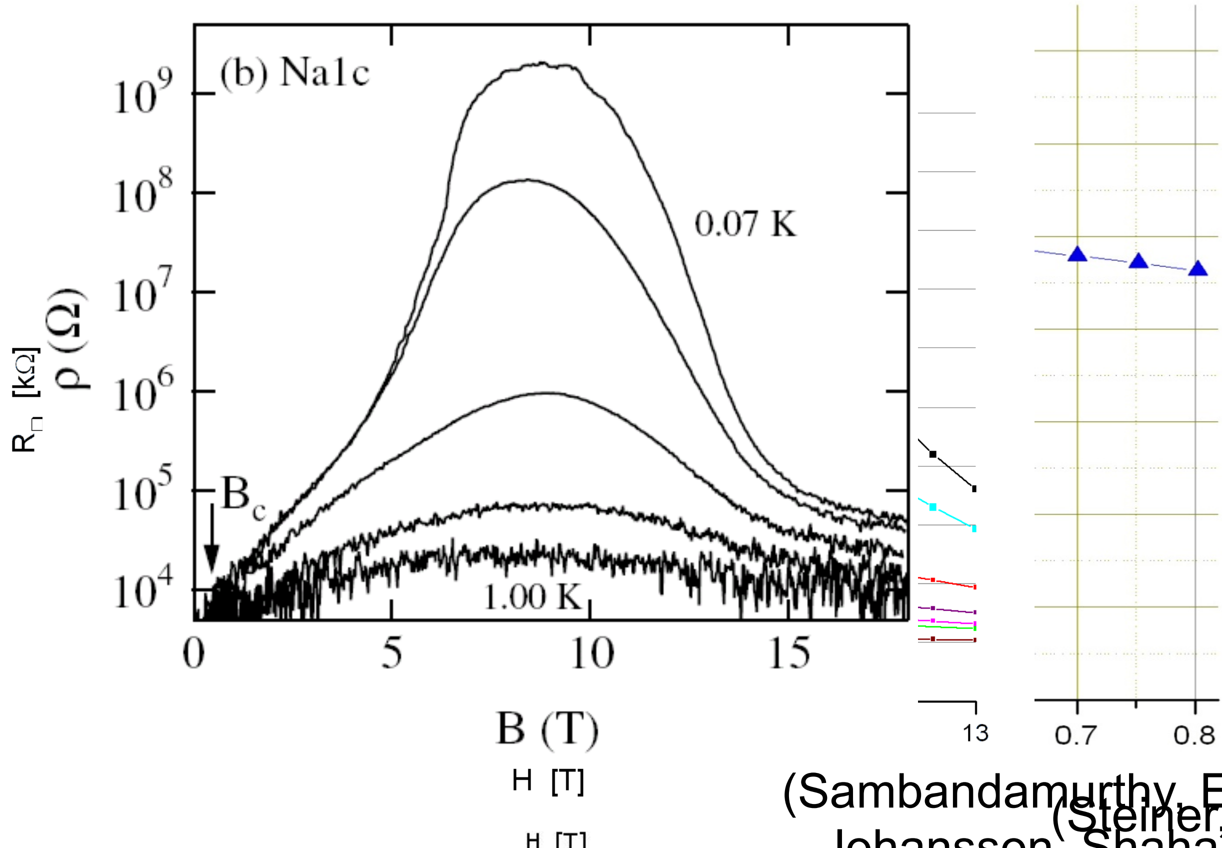


(Hebard, Paalanen, PRL 1990)

Observation of Superconductor-insulator transition

• Thin amorphous films: B tunes a SC-Insulator transition.

InO:



(Sambandamurthy, Engel, Johansson, Shahar, PRL 2004)

(Steiner, Kapitulnik)

• Saturation as T → 0

• Insulating peak different from sample to sample, scaling different – log, activated.

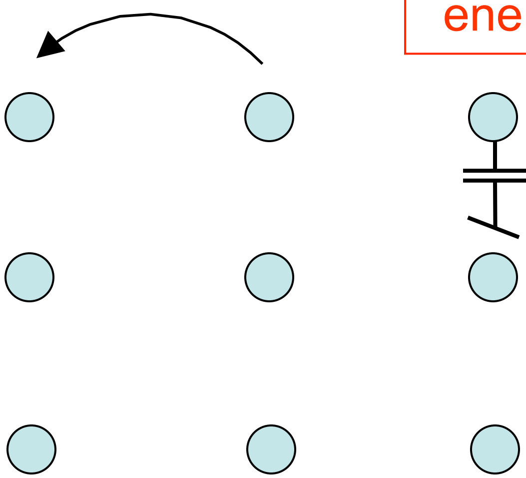
Vortex Paradigm

X-Y model for superconducting film: Cooper pairs as Bosons

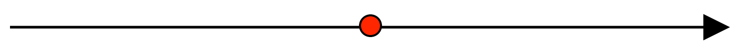
- When the superconducting order is strong – ignore electronic excitations.
- Standard model for bosonic SF-Ins transition – "Bose-Hubbard model":

$$\boxed{H = \sum_i \left\{ -\sum_j \rho_s \cos(\nabla_j \phi_i) + U\hat{n}_i^2 \right\}}$$

$$[\hat{n}, \phi] = -i$$



- Large U - Mott insulator (no charge fluctuations)
- Large ρ_s - Superfluid (intense charge fluctuations, no phase fluctuations)



Vortex description of the SF-insulator transition

(Fisher, 1990)

• Vortex hopping: (result of charging effects)

$$-t_V \cos(\nabla_j \hat{\theta}_i)$$

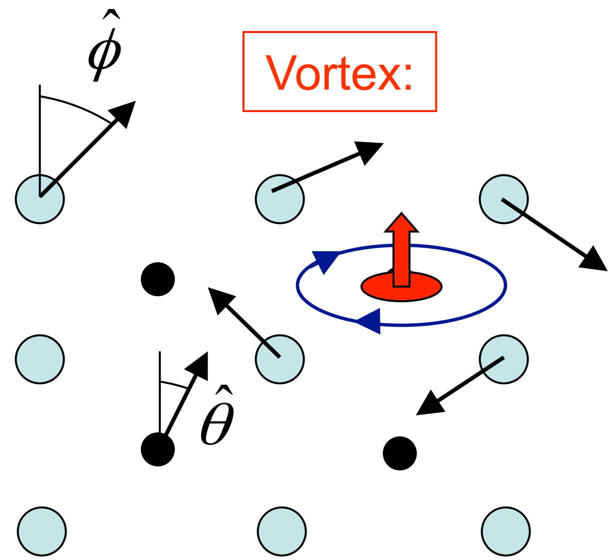
$$[\hat{n}_V, \theta] = -i$$

• Vortex-vortex interactions:

$$\frac{1}{2}\rho_s \sum_{i,j} n_{V\,i} \cdot n_{V\,j} \cdot \ln|\vec{x}_i - \vec{x}_j|$$

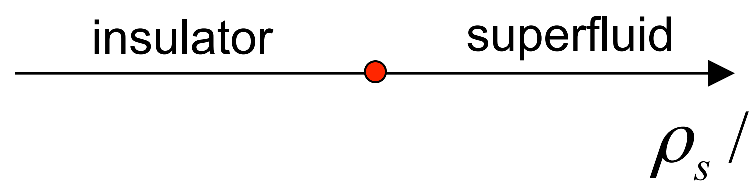
Condensed vortices

= insulating CP’s

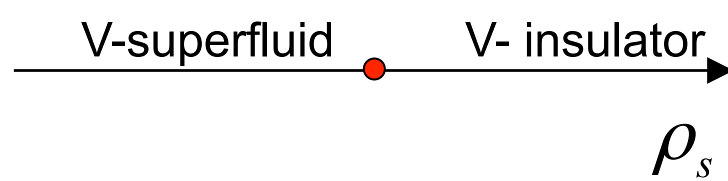


Vortex:

Cooper-pairs:

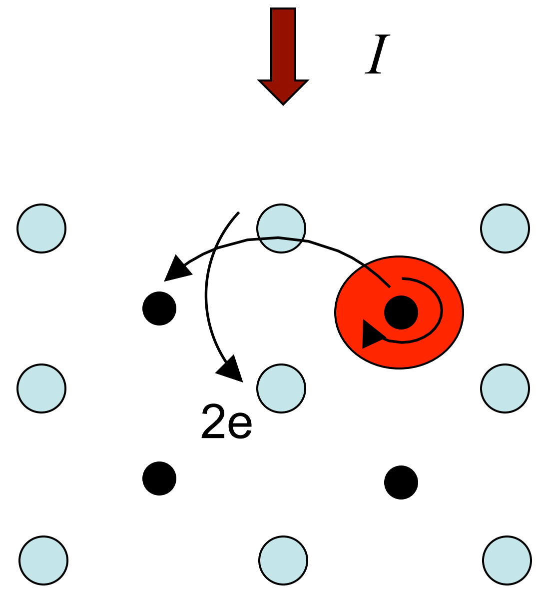


Vortices:



Universal (?) resistance at SF-insulator transition

Assume that vortices and Cooper-pairs are self dual at transition point.



- Current due to CP hopping: $I = \dfrac{2e}{\tau}$
- EMF due to vortex hopping:

$$\frac{\hbar}{2e}\Delta\dot{\phi} = \Delta V \quad \Rightarrow \quad \Delta V = \frac{\hbar}{2e}\frac{2\pi}{\tau}$$

- Resistance: $\boxed{R = \dfrac{V}{I} = \dfrac{2\pi\hbar}{2e\tau}\Big/\dfrac{2e}{\tau} = \dfrac{h}{4e^2} = 6.5k\Omega}$

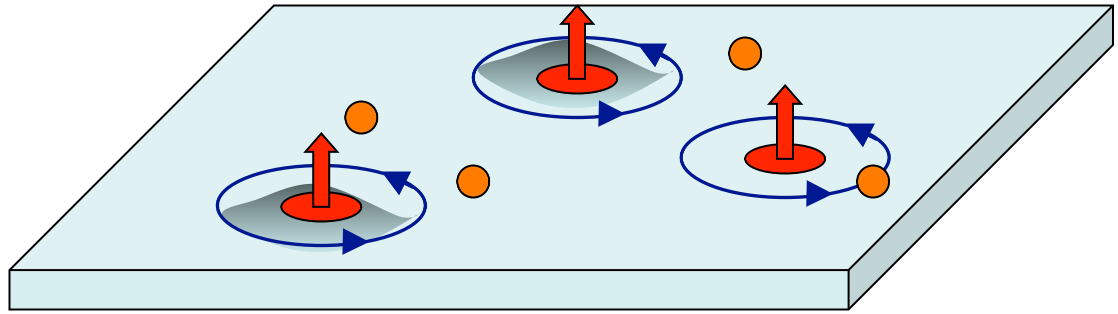
In reality superconducting films are not self dual:

- vortices interact logarithmically, Cooper-pairs interact at most with power law.
- Samples are very disordered and the disorder is different for cooper-pairs and vortices.

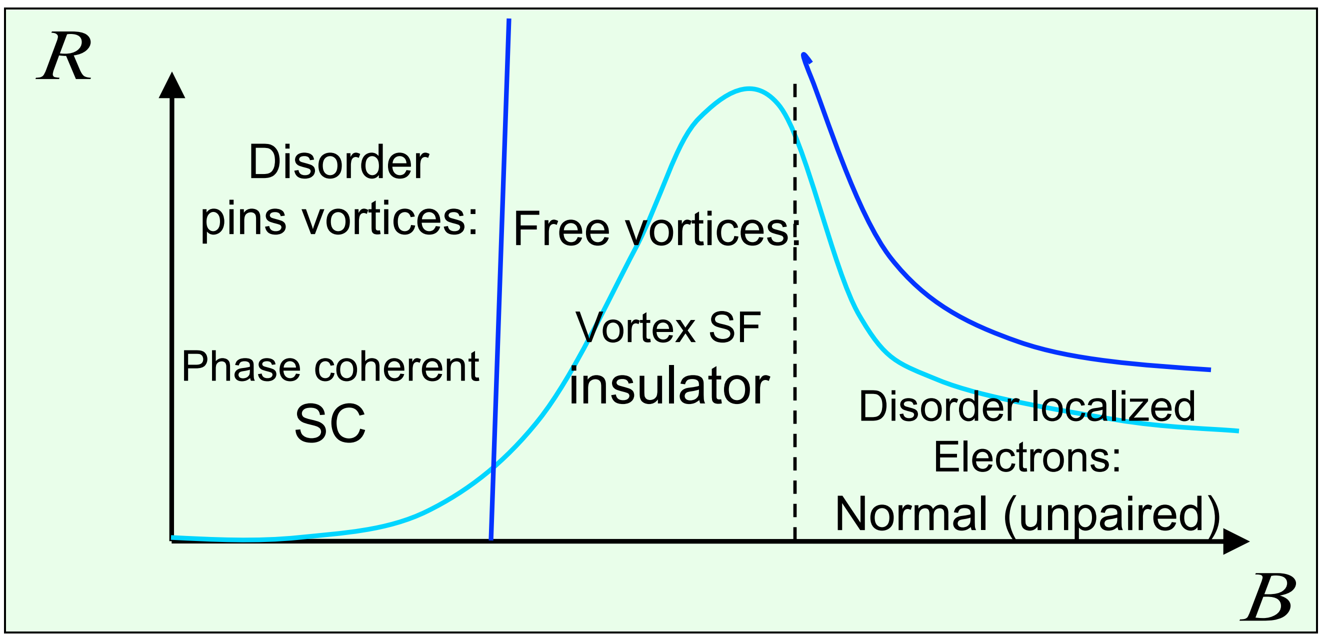
Magnetically tuned Superconductor-insulator transition

- Net vortex density:

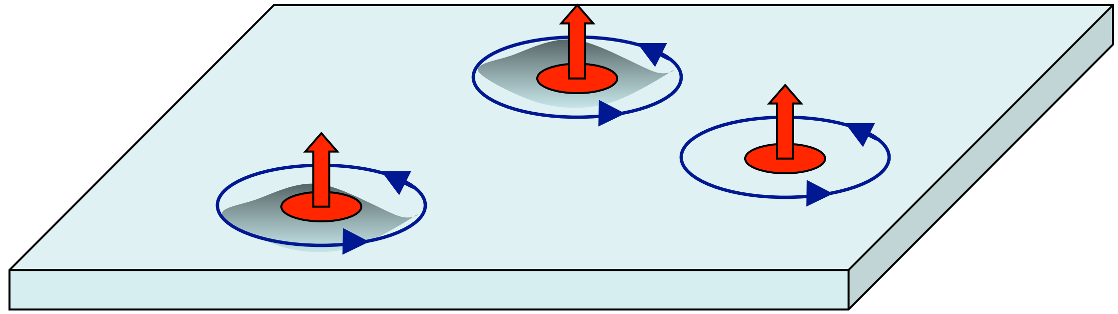
$$\frac{h}{2e}\left\langle \hat{n}_V \right\rangle = B$$



- Disorder pins vortices for small field – **superconducting phase.**
- Large fields some free vortices appear and condense – **insulating phase.**
- Larger fields superconductivity is destroyed – **normal (unpaired) phase.**



Magnetically tuned Superconductor-insulator transition

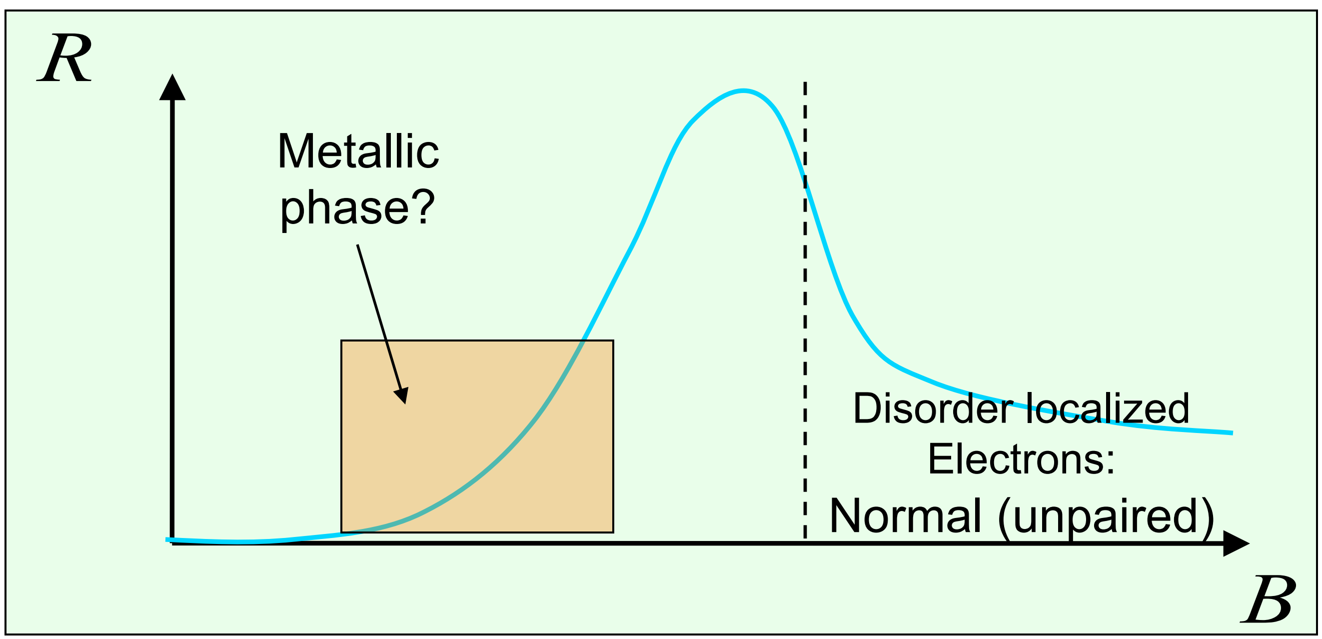


- Net vortex density:

$$\frac{h}{2e}\langle \hat{n}_V \rangle = B$$

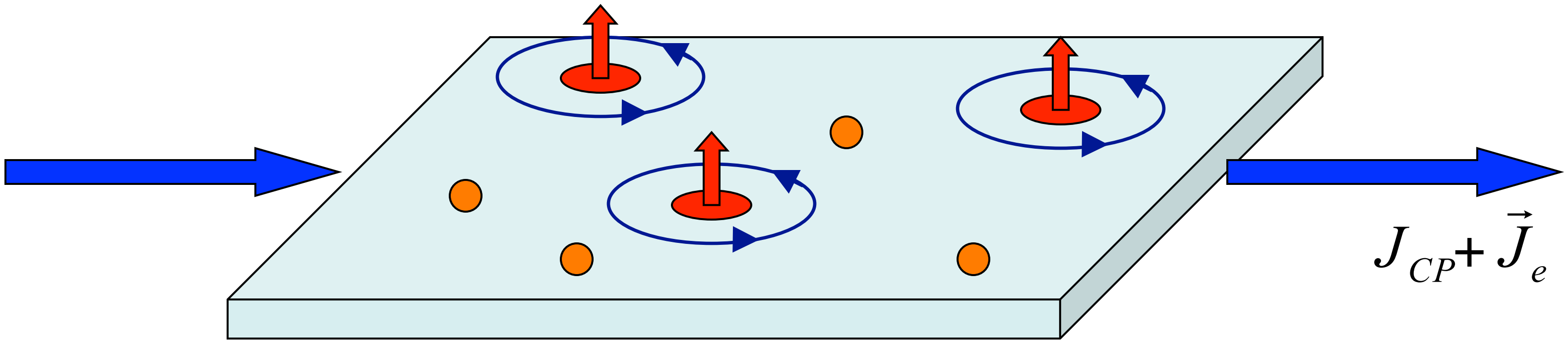
Problems

- Saturation of the resistance – 'metallic phase'
- Non-universal insulating peak – completely different depending on disorder.

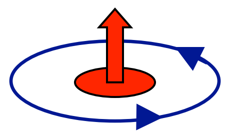


Two-fluid model for the SC-Metal-Insulator transition

(Galitski, Refael, Fisher, Senthil, 2005)



Uncondensed vortices:
Cooper-pair channel



Disorder induced Gapless QP's
(electron channel)

(delocalized core states?)

$$\boxed{\vec{J}_e = \sigma_e \vec{E}}$$

Finite conductivity:

$$\vec{j}_V = \sigma_V \vec{F}_V \Rightarrow \boxed{\frac{1}{\sigma_V}\vec{E} = \vec{J}_{CP}}$$

$$F_V = \hat{z} \times \vec{J}_{CP}$$

$$\hat{z} \times \vec{E} = \vec{j}_V$$

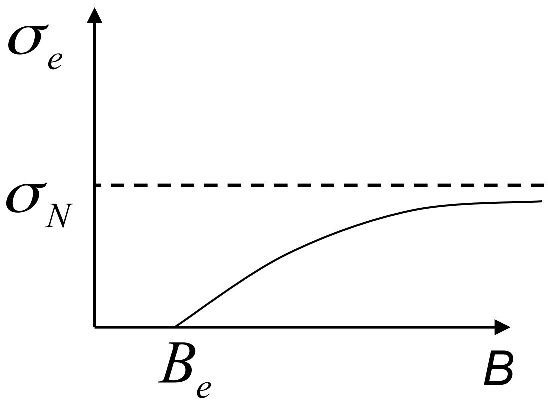
Two channels in parallel:

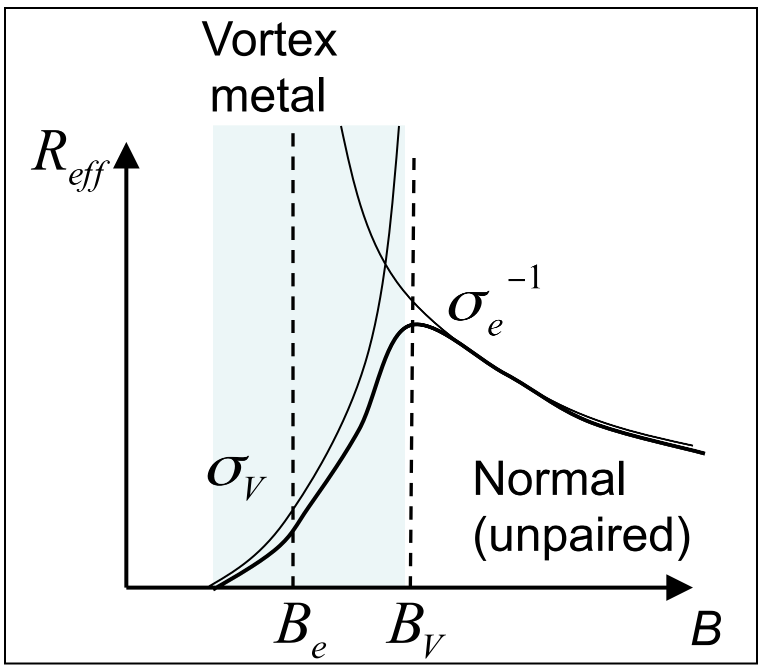
$$\boxed{\vec{J} = (\sigma_e + \sigma_V^{-1})\vec{E}}$$

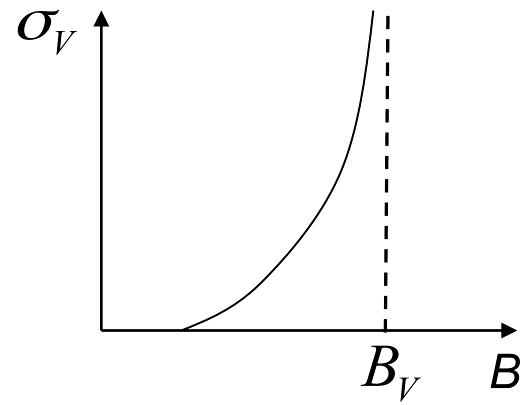
Transport properties of the vortex-metal

Effective conductivity: $\boxed{\sigma_{eff} = \sigma_e + \sigma_V^{-1}}$

- **Assume:**
  - σ_e grows from zero to σ_N.
  - σ_V grows from zero to infinity.



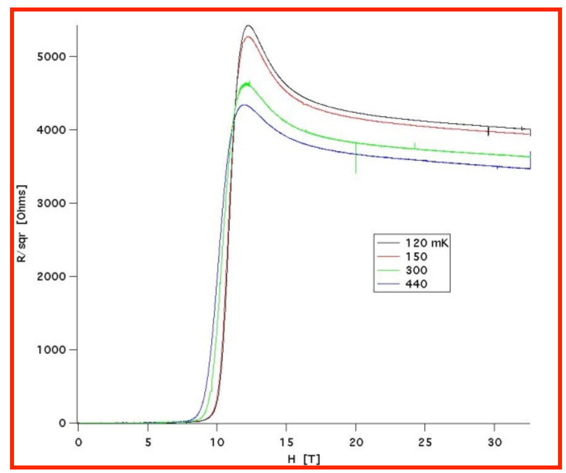




Weak insulators:

Ta, MoGe
Weak InO

$B_e < B_V$

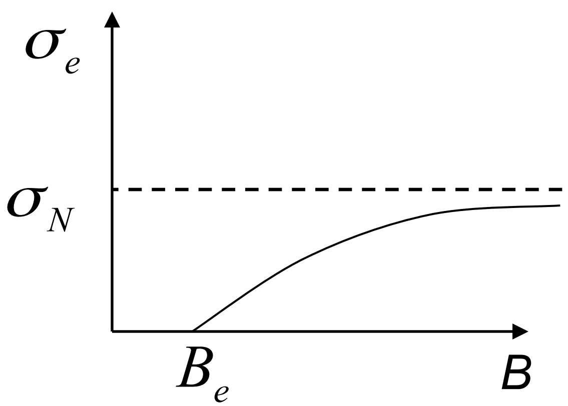


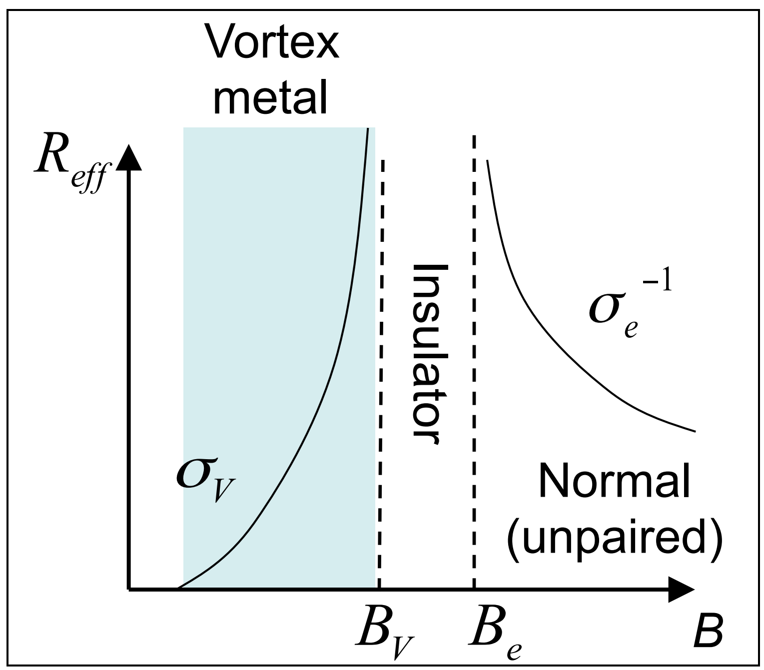
Transport properties of the vortex-metal

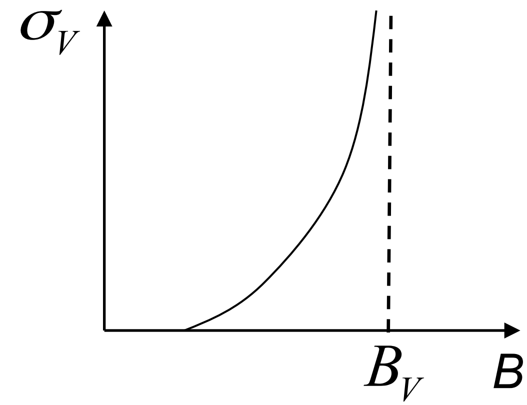
Effective conductivity: $\boxed{\sigma_{eff} = \sigma_e + \sigma_V^{-1}}$

Chargless spinons contribute to conductivity!

- Assume:
  - σ_e grows from zero to σ_N.
  - σ_V grows from zero to infinity.



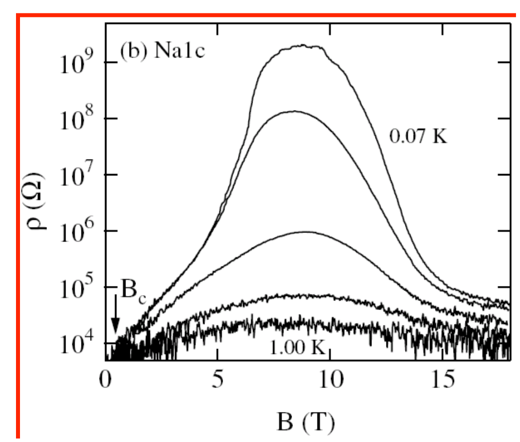




Strong insulators:

TiN, InO

$B_e > B_V$

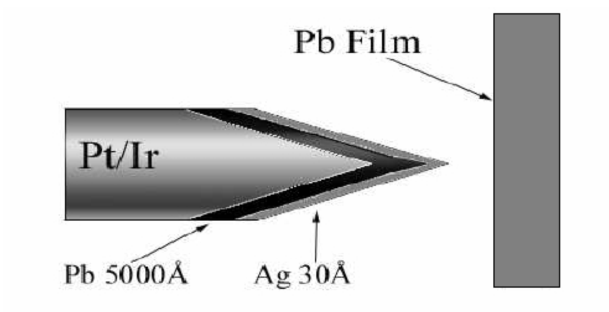


More physical properties of the vortex metal

Cooper pair tunneling

• A superconducting STM can tunnel Cooper pairs to the film:

$$\boxed{G = G_{2e} + G_{CP}}$$



(Naaman, Tyzer, Dynes, 2001).

More physical properties of the vortex metal

Cooper pair tunneling

- A superconducting STM can tunnel Cooper pairs to the film:

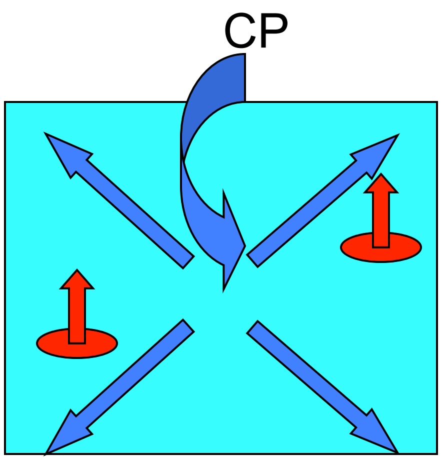
$$\boxed{G = G_{2e} + G_{CP}}$$

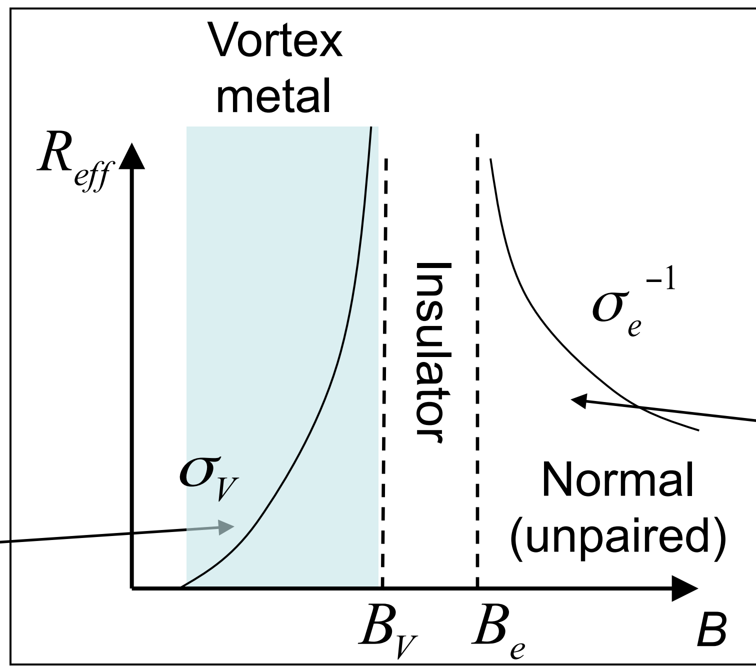
Vortex metal phase:

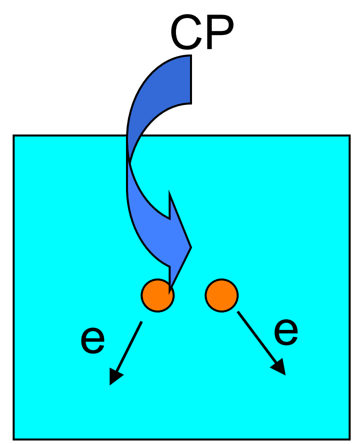
$$\boxed{G_{CP} \sim \frac{1}{T^2} \exp(-\sigma_V \ln^2 T)}$$

Normal phase:

$$\boxed{G_{2e} \sim \sigma_e^{\;2}}$$







$G \approx G_{CP}$
strongly T dependent

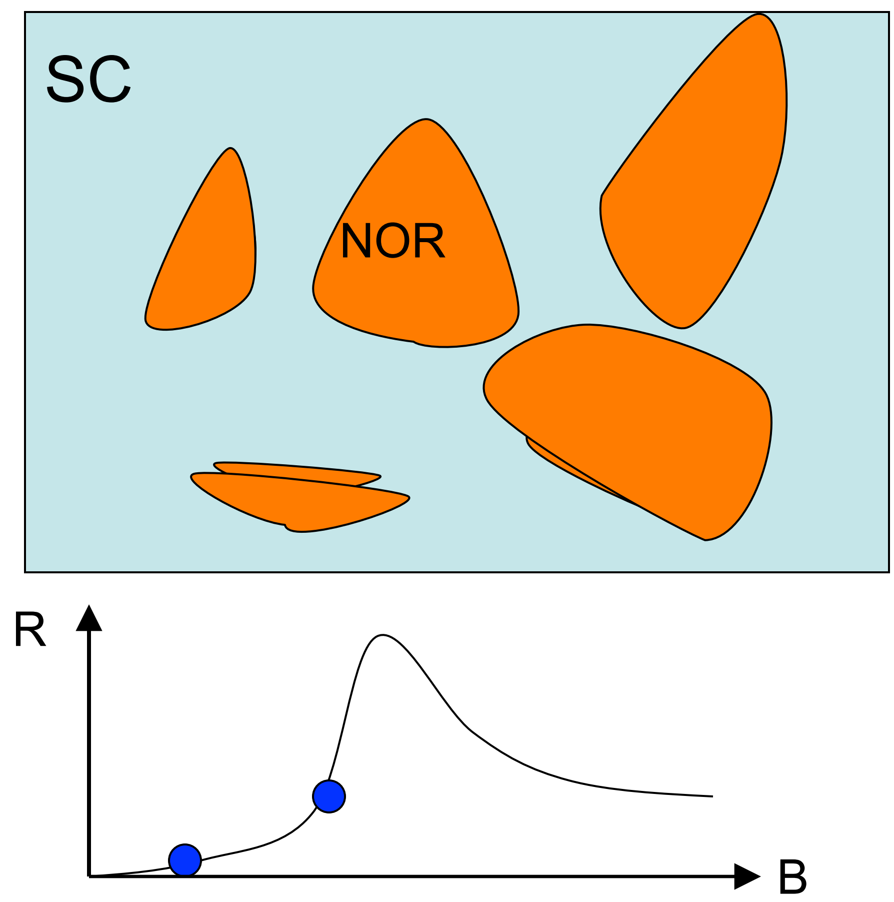
$G \approx G_{2e}$
$\sim 1/\ln^2 T$

Percolation Paradigm

(Trivedi,
Dubi, Meir, Avishai,
Spivak, Kivelson,
et al.)

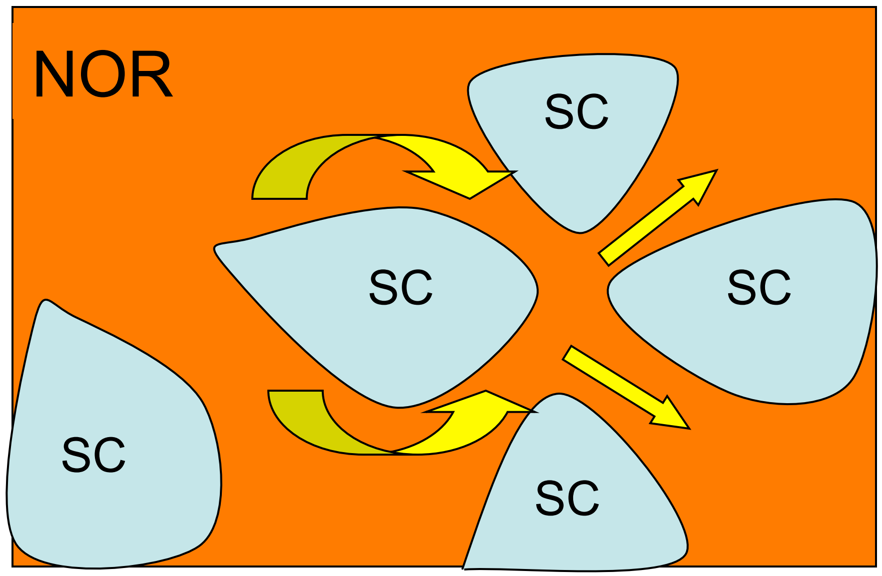
Pardigm II: superconducting vs. Normal regions percolation

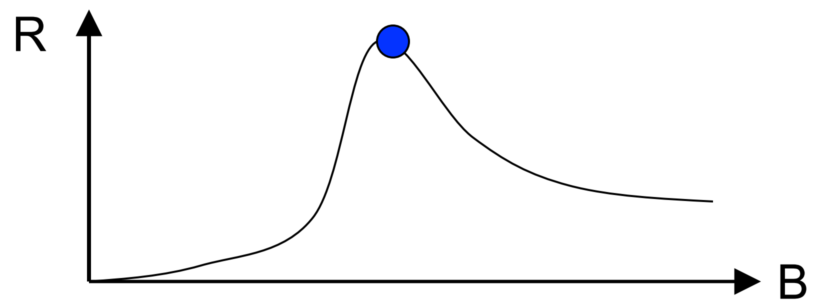
• Strong disorder breaks the film into superconducting and normal regions.



Pardigm II: superconducting vs. Normal regions percolation

• Strong disorder breaks the film into superconducting and normal regions.

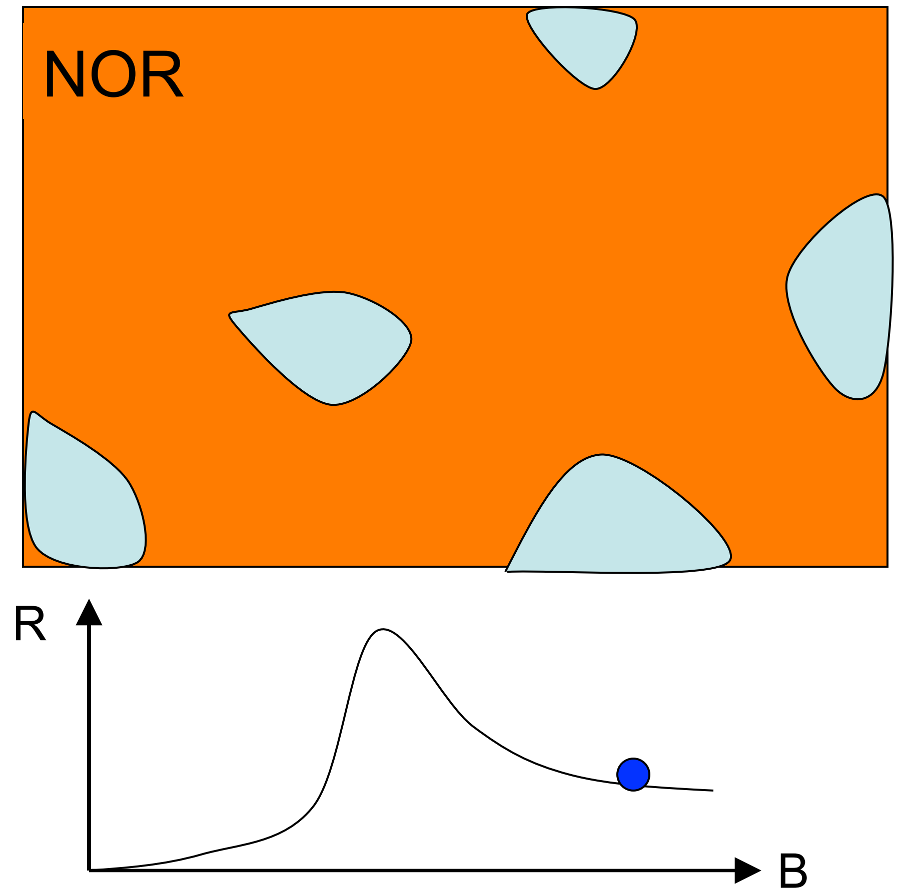




• Near percolation – thin channels of the disorder-localized normal phase.

Pardigm II: superconducting vs. Normal regions percolation

• Strong disorder breaks the film into superconducting and normal regions.



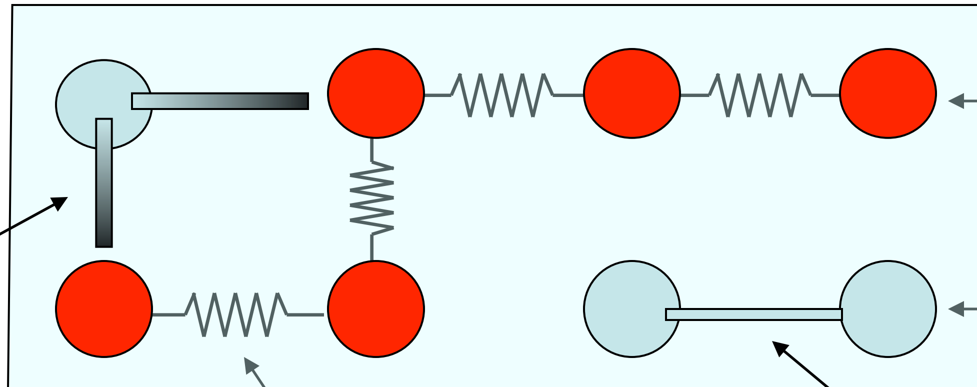
• Near percolation – thin channels of the disorder-localized normal phase.

• Far from percolation – disordered localized normal electrons.

Magneto-resistance curves in the percolation picture

(Dubi, Meir, Avishai, 2006)

- Simulate film as a resistor network:



NOR island

SC island

Nor-SC links:

$$R \sim R_0 e^{E_G/T}$$

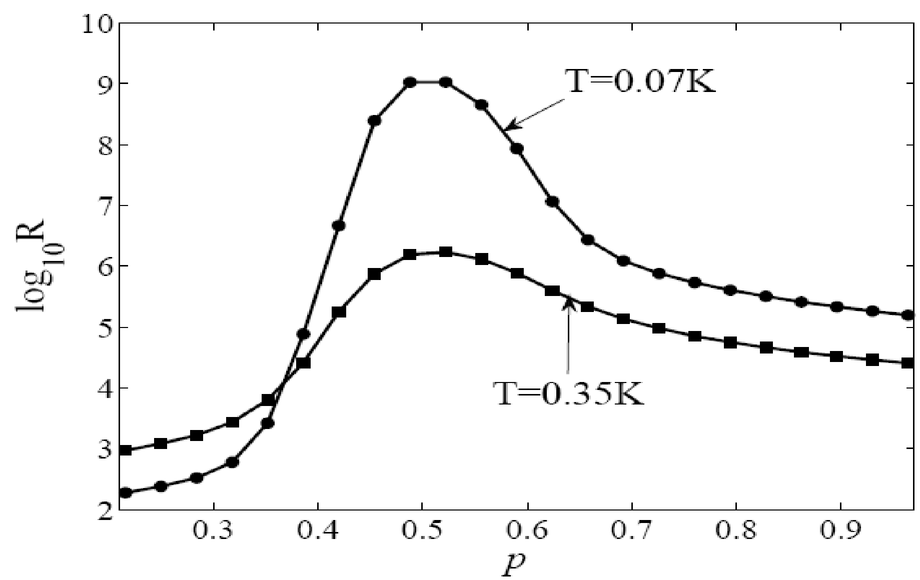
Normal links:

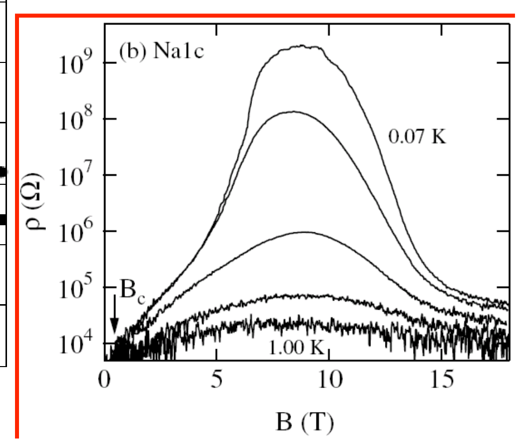
$$R \sim R_0 e^{(|\varepsilon_1|+|\varepsilon_2|+|\varepsilon_1-\varepsilon_2|)/kT}$$

SC-SC links:

$$R \sim T^{\alpha}$$

Reuslting MR:



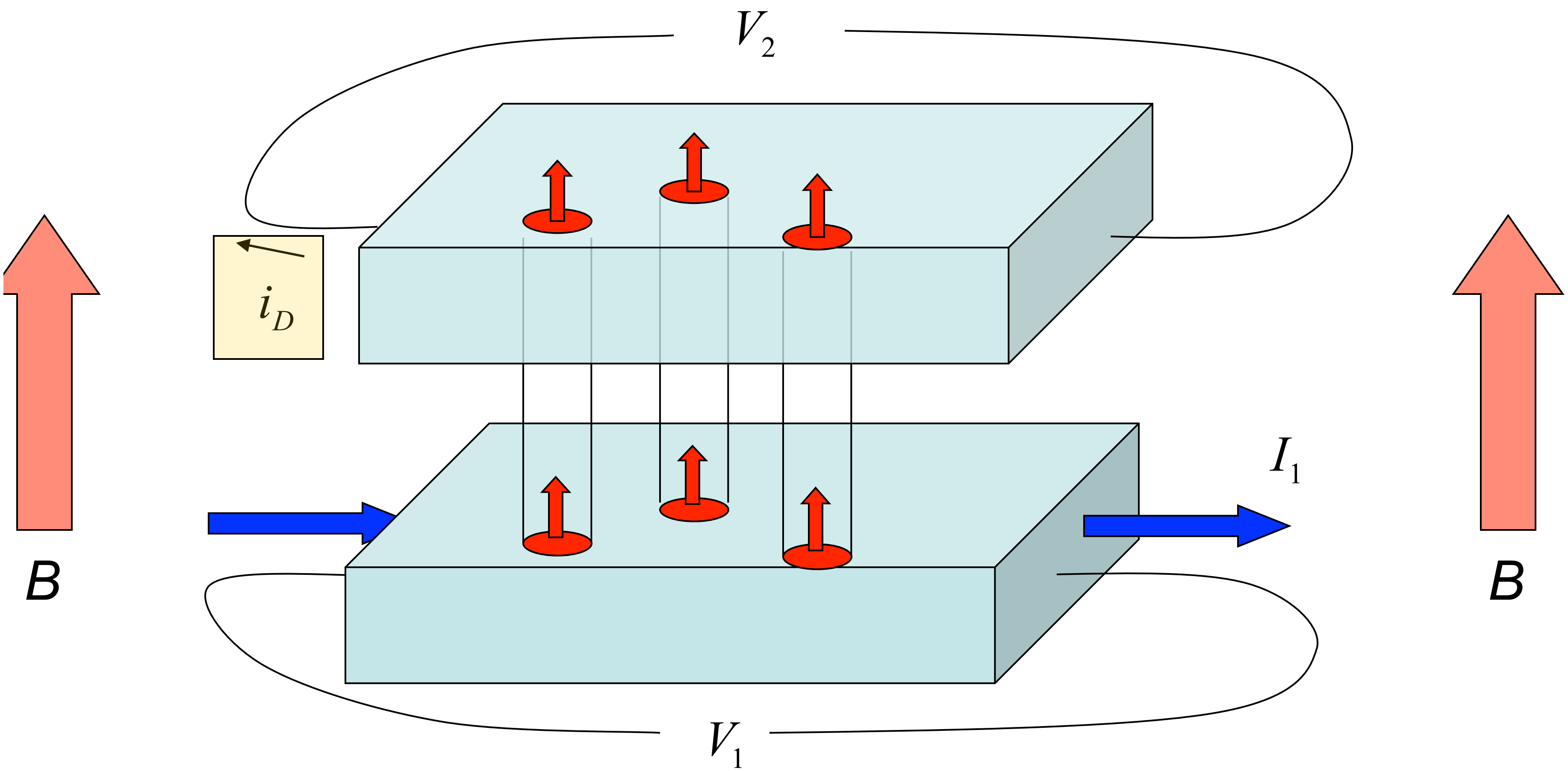


Drag in a bilayer system

Giaever transformer – Vortex drag

(Giaever, 1965)

Two type-II bulk superconductors:



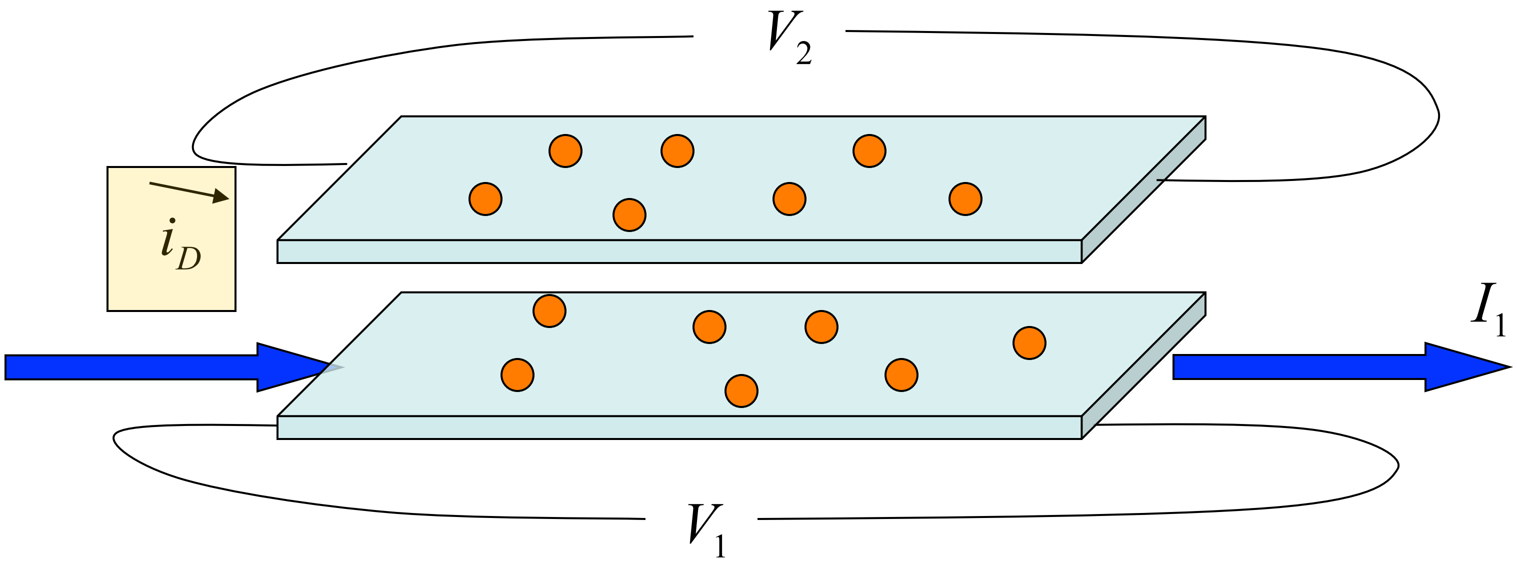
Vortices tightly bound:

$$V_2 = V_1$$

$$\boxed{R_D = \frac{V_2}{I_1}}$$

2DEG bilayers – Coulomb drag

Two thin electron gases: $R_D = \dfrac{V_2}{I_1}$



• Coulomb force creates friction between the layers.

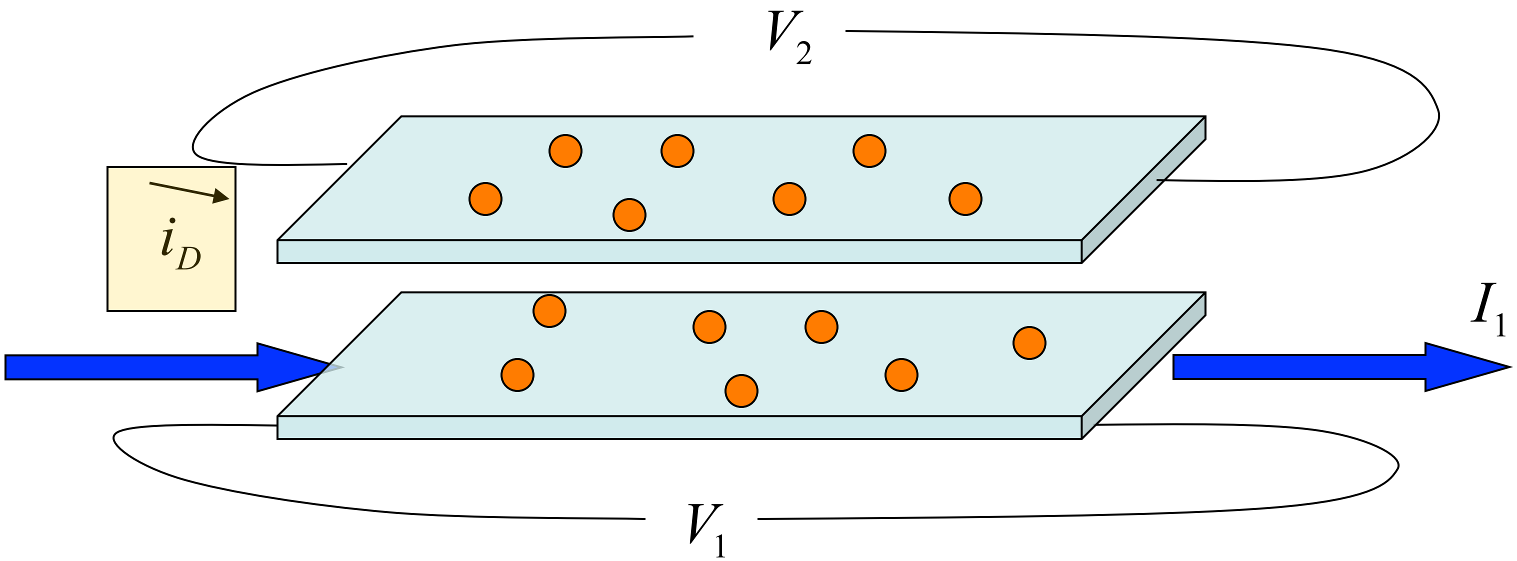
• Inversely proportional to density squared: $\boxed{R_D \propto \dfrac{1}{n_e^2}}$

• Opposite sign to Giaever's vortex drag.

2DEG bilayers – Coulomb drag

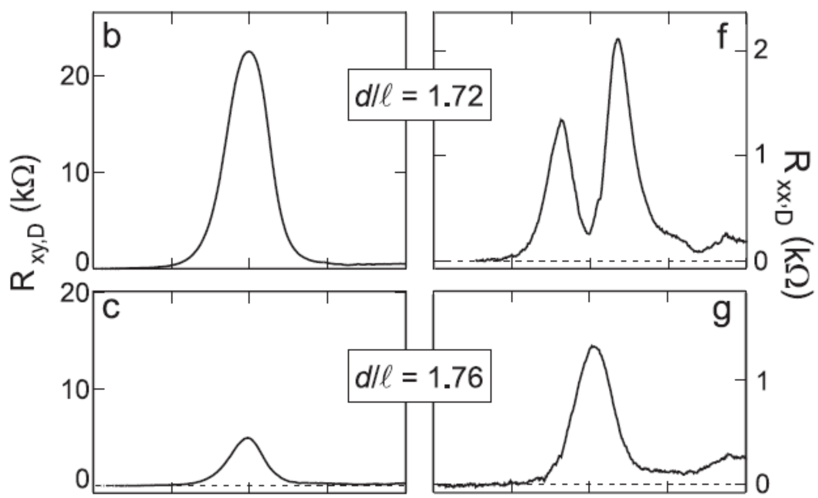
Two thin electron gases:

$$R_D = \frac{V_2}{I_1}$$



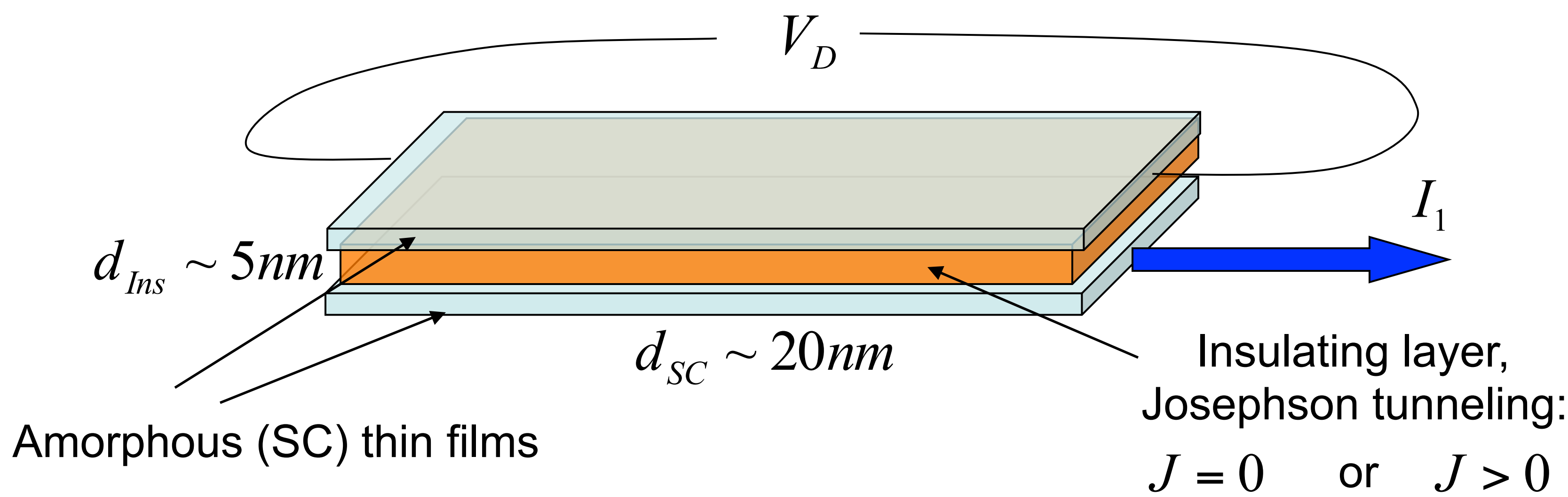
Example:

$\nu_T = 1$ “Excitonic condensate”



(Kellogg, Eisenstein, Pfeiffer, West, 2002)

Thin film Giaever transformer



Percolation paradigm

- Drag is due to coulomb interaction.
- Electron density:

$$n_{2d} \sim d_{SC} \cdot 10^{20} cm^{-3} \rightarrow 2 \cdot 10^{14} cm^{-2}$$

(QH bilayers: $n_{2d} \sim 5 \cdot 10^{10} cm^{-2}$)

Drag suppressed

?

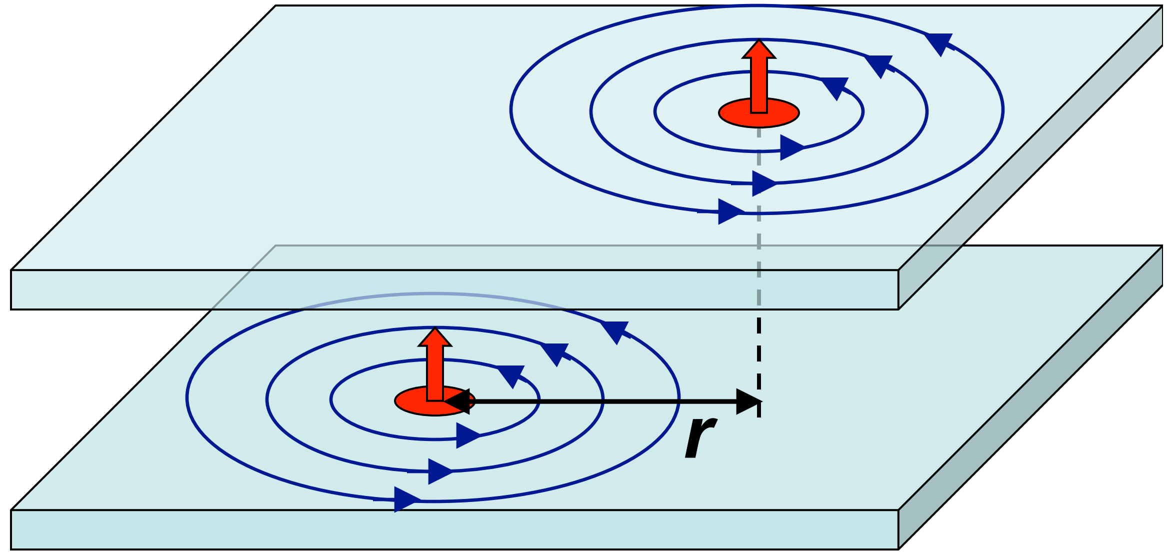
Vortex condensation paradigm

- Drag is due to inductive current interactions, and Josephson coupling.
- Vortex density:

$$n_V \sim \frac{B}{\phi_0} \sim (10^{11} \cdot B_{[T]}) cm^{-2}$$

Significant Drag

Vortex drag in thin films bilayers: interlayer interaction



- Vortex current suppressed.

e.g., Pearl penetration length:

$$\lambda_{eff} = \frac{2\lambda_L^{\ 2}}{d_{SC}}$$

- Vortex attraction=interlayer induction.
  Also suppressed due to thinness.

$$U_{\text{inter}}(q) \approx \boxed{\frac{\phi_0^{\ 2}}{2\pi\lambda_{eff}^{\ 2}}} \frac{e^{-qa}}{q[(q+\lambda_{eff}^{\ -1})^2 - e^{-2qa}/\lambda_{eff}^2]}$$

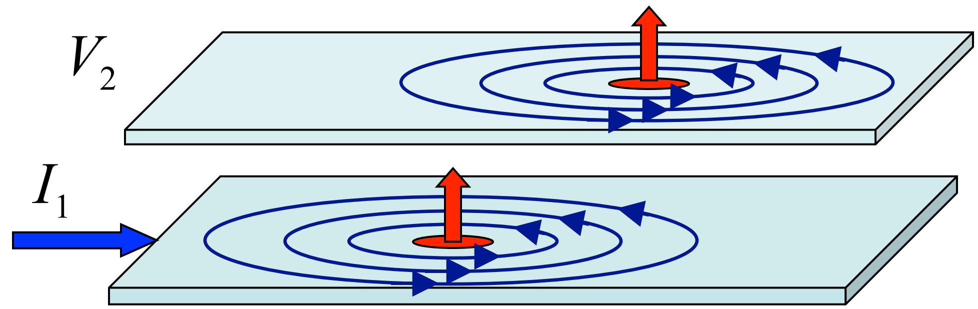
$$\propto d_{SC}^{\ 2}$$

$$\sim \frac{\phi_0^{\ 2}}{4\pi\lambda_{eff}} \ln(r), \quad r > \lambda_{eff}$$

$$\sim \frac{\phi_0^{\ 2}}{4\lambda_{eff}^{\ 2}} \frac{r^2}{a}, \quad r < a$$

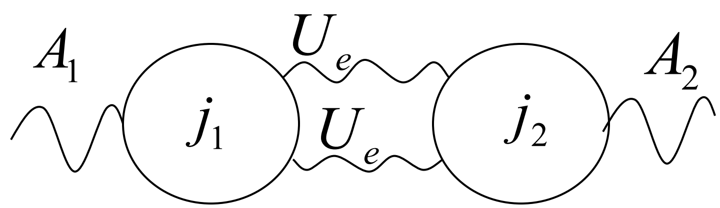
Vortex drag in thin films within vortex metal theory

- $R_D = \dfrac{V_2}{I_1}$



- Perturbatively:

$$R_D = G_V^{drag} \sim [j_1, j_2]$$



(Kamenev, Oreg)

- Expect: $G_V^{drag} \propto \dfrac{\partial\sigma_{V1}}{\partial n_{V1}} \cdot \dfrac{\partial\sigma_{V2}}{\partial n_{V2}} \Rightarrow \boxed{\propto \dfrac{\partial R_1}{\partial B} \cdot \dfrac{\partial R_2}{\partial B}}$

Drag generically proportional to MR slope.

(Following von Oppen, Simon, Stern, PRL 2001)

- Answer:

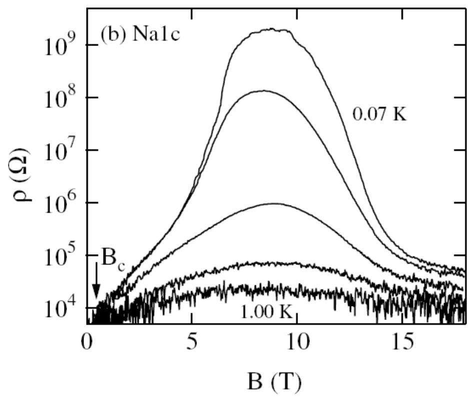
$$\boxed{R_D = G_V^{drag} = \frac{e^2 \phi_0^{\,2}}{8\pi^4 T} \frac{\partial R_1}{\partial B} \frac{\partial R_2}{\partial B} \int d\omega \int dq\, q^3\, |U|^2 \frac{\operatorname{Im}\chi_1 \operatorname{Im}\chi_2}{\sinh^2(\omega/2T)}}$$

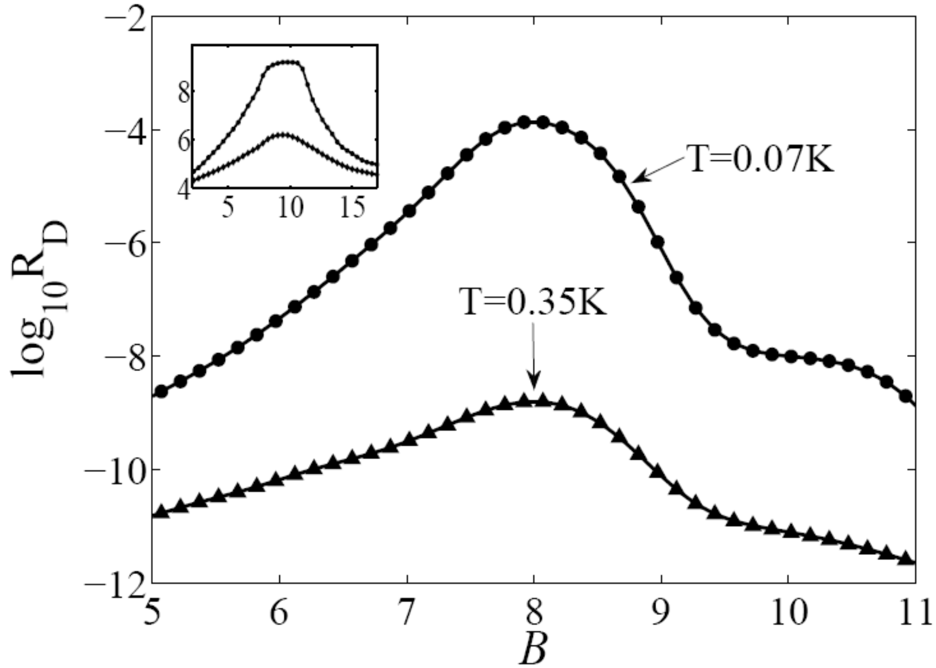
U – **screened** inter-layer potential. χ - Density response function (diffusive FL)

Vortex drag in thin films: Results

$$R_D = G_V^{drag} = \frac{e^2\phi_0^2}{8\pi^4 T}\frac{\partial R_1}{\partial B}\frac{\partial R_2}{\partial B}\int d\omega \int dq\, q^3\, |U|^2\, \frac{\mathrm{Im}\,\chi_1\, \mathrm{Im}\,\chi_2}{\sinh^2(\omega/2T)}$$

- Our best chance (with no J tunneling) is the highly insulating InO:





- maximum drag:

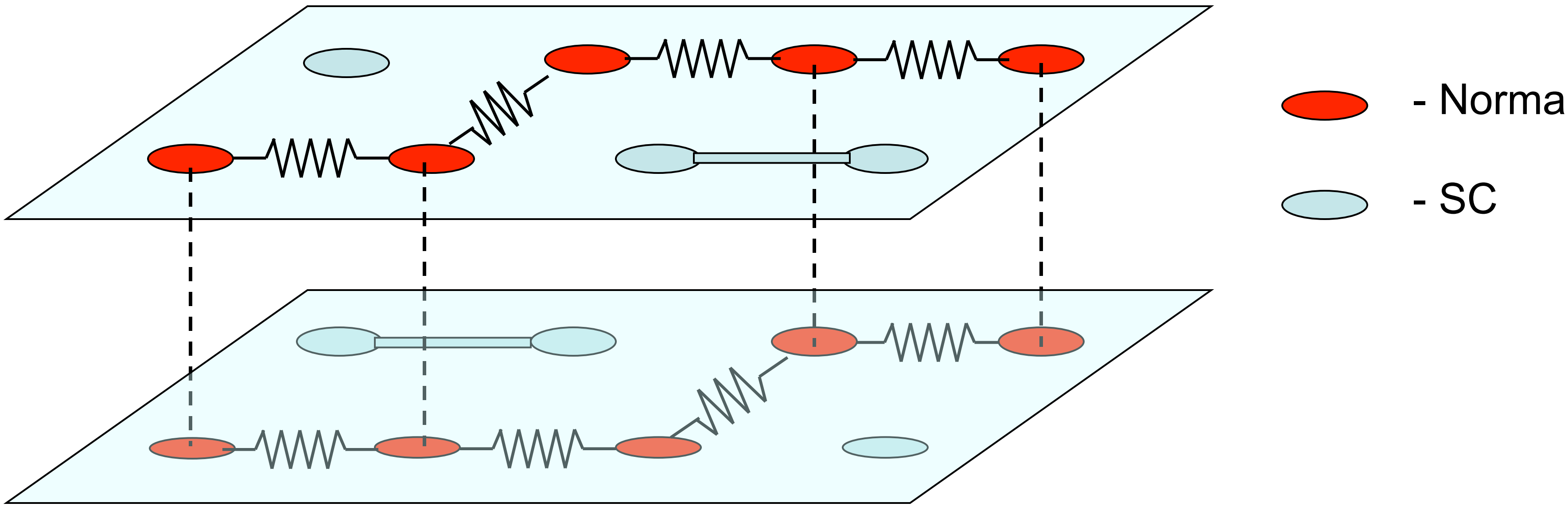
$$R_D^{\max} \sim 0.1 m\Omega$$

Note: similar analysis for SC-metal ‘bilayer’ using a ground plane.

Experiment: Mason, Kapitulnik (2001) Theory: Michaeli, Finkel’stein, (2006)

Percolation picture: Coulomb drag

- Solve a 2-layer resistor network with drag.



- Can neglect drag with the SC islands:

$$R^{D}_{SC-SC} \;,\; R^{D}_{SC-NOR} \approx 0$$

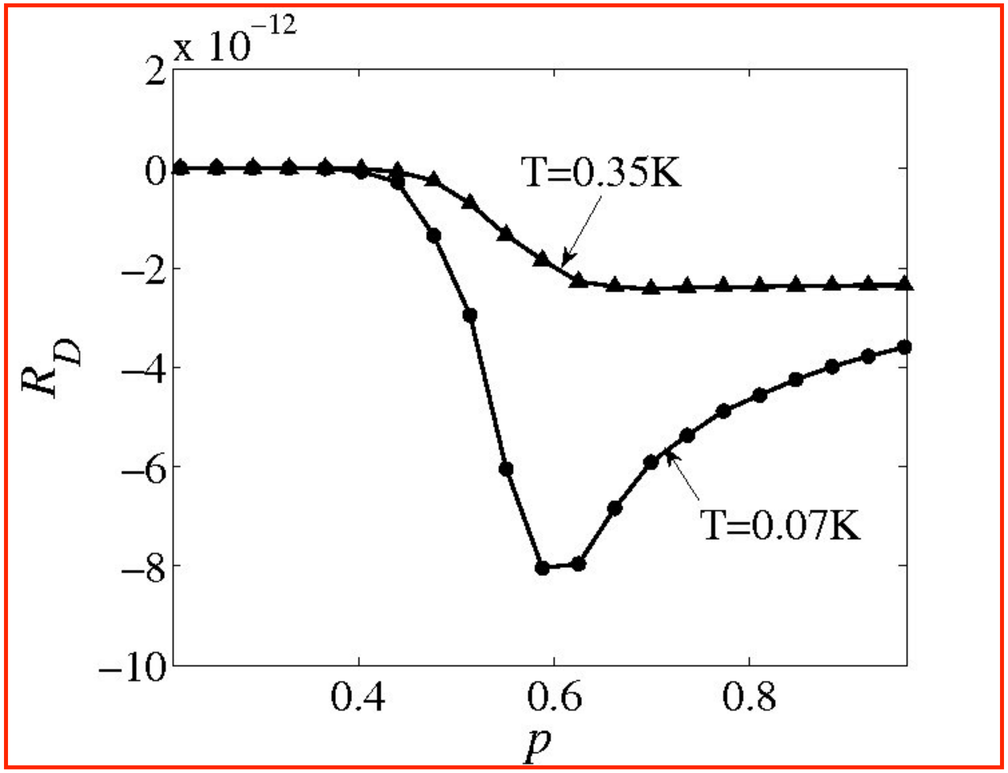
- Normal-Normal drag – use results for disorder localized electron glass:

$$R^{D}_{NOR-NOR} = \frac{1}{96\pi^2}\frac{R_1 R_2}{\hbar/e^2}\frac{T^2}{(e^2 n_e\, a\, d_{film})^2}\ln\frac{1}{2x_0}$$

(Shimshoni, PRB 1994)

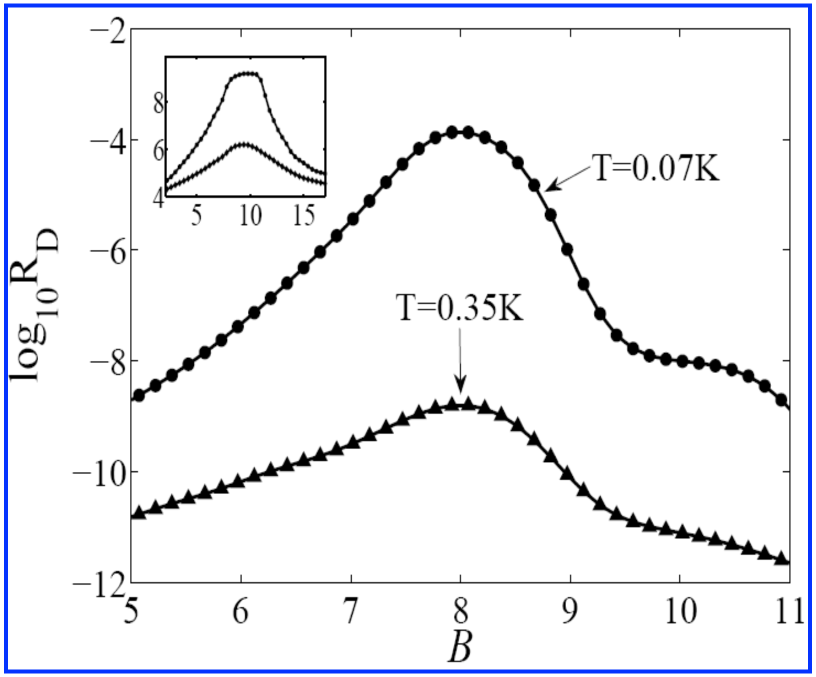
Percolation picture: Results

• Solution of the random resistor network:



?

Compare to vortex drag:



Conclusions

- Vortex picture and the puddle picture: similar single layer predictions.

- Giaever transformer bilayer geometry may qualitatively distinguish:

  Large drag for vortices, small drag for electrons, with opposite signs.

- Drag in the limit of zero interlayer tunneling:

$$\boxed{R_D^{vortex} \sim 0.1 m\Omega \quad \text{vs.} \quad R_D^{percolation} \sim 10^{-11}\Omega}$$

- Intelayer Josephson should increase both values, and enhance the effect. (future theoretical work)

- Amorphous thin-film bilayers will yield interesting complementary information about the SIT.

Conclusions

- What induces the gigantic resistance and the SC-insulating transition?

- What is the nature of the insulating state? Exotic vortex physics?

Phenomenology:

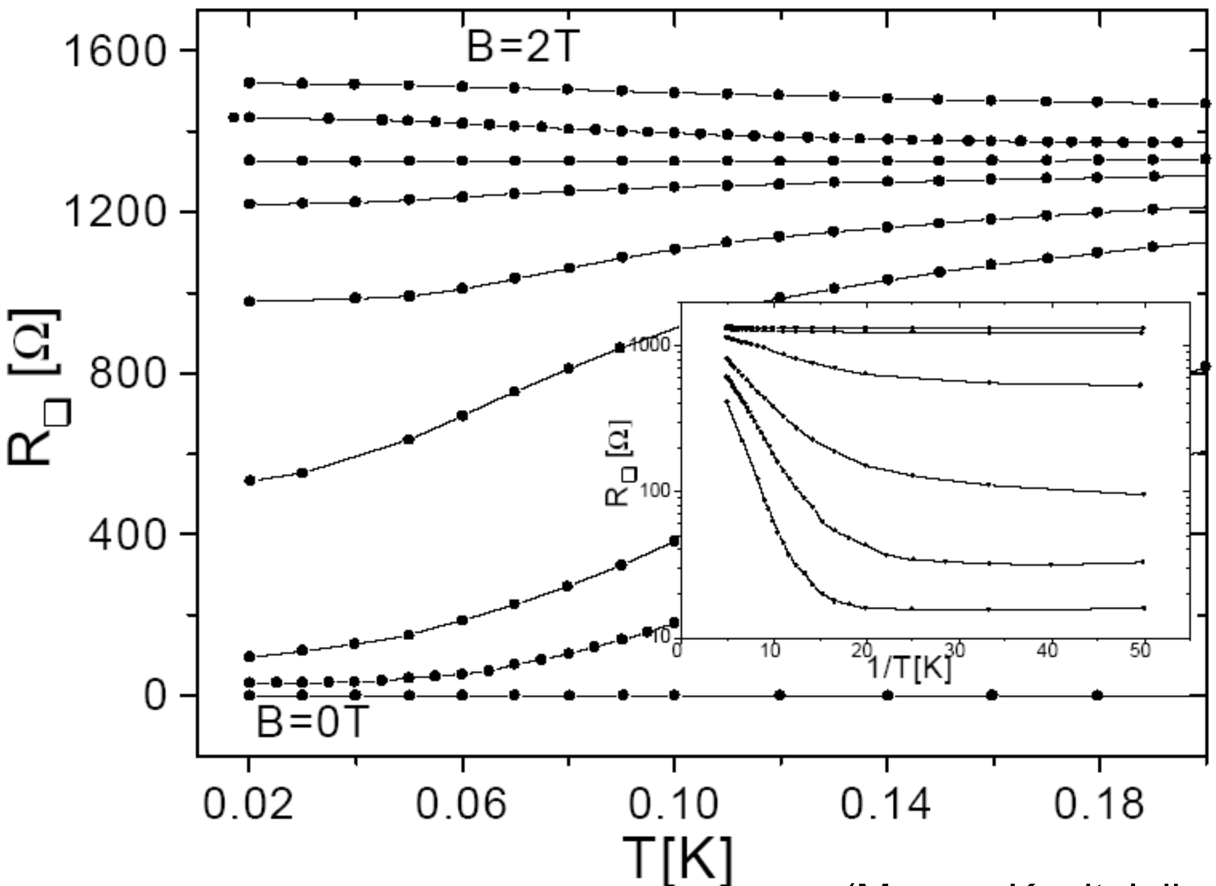
- Vortex picture and the puddle picture: similar single layer predictions.

Experimental suggestion:

- Giaever transformer bilayer geometry may qualitatively distinguish:
  Large drag for vortices, small drag for electrons.

Observation of a metallic phase

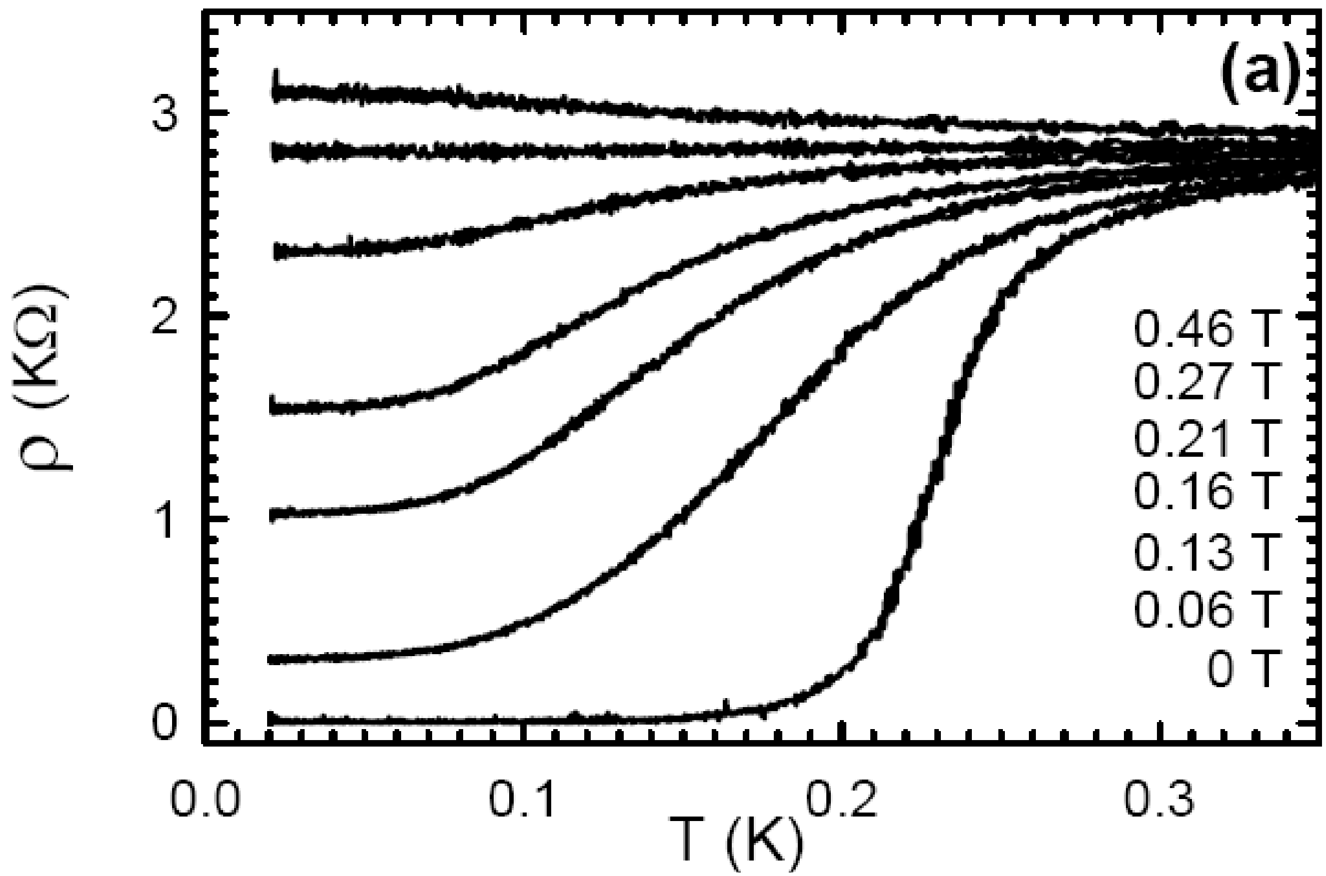
• MoGe:



(Mason, Kapitulnik, PRB 1999)

Observation of a metallic phase

• Ta:

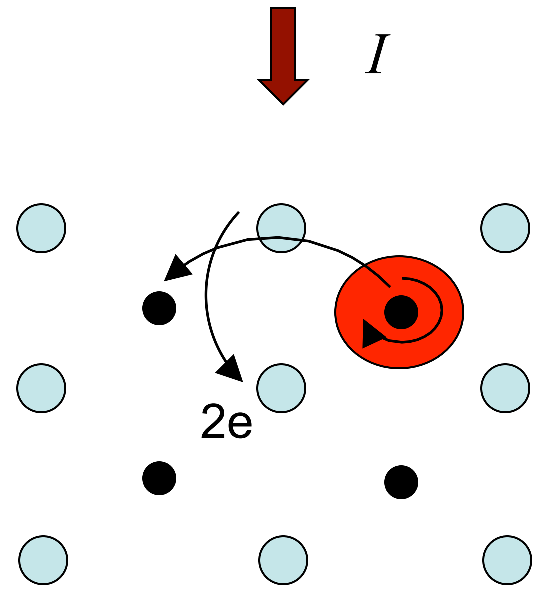


(Qin, Vicente, Yoon, 2006)

• Saturation at ~100mK: New metalic phase? (or saturation of electrons temperature)

Universal (?) resistance at SF-insulator transition

Assume that vortices and Cooper-pairs are self dual at transition point.



- Current due to CP hopping: $I = \dfrac{2e}{\tau}$

- EMF due to vortex hopping:

$$\frac{\hbar}{2e}\Delta\dot{\phi} = \Delta V \quad \Rightarrow \quad \Delta V = \frac{\hbar}{2e}\frac{2\pi}{\tau}$$

- Resistance: $\boxed{R = \dfrac{V}{I} = \dfrac{2\pi\hbar}{2e\tau}\Big/\dfrac{2e}{\tau} = \dfrac{h}{4e^2} = 6.5k\Omega}$

In reality superconducting films are not self dual:

- vortices interact logarithmically, Cooper-pairs interact at most with power law.

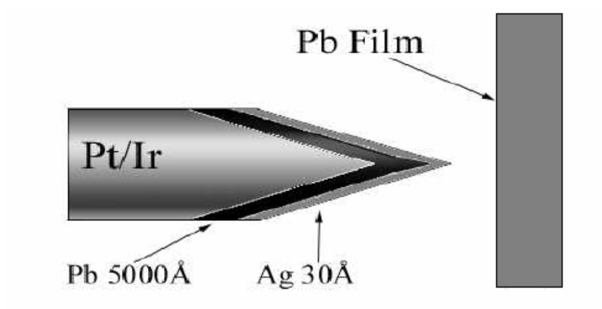
- Samples are very disordered and the disorder is different for cooper-pairs and vortices.

More physical properties of the vortex metal

Cooper pair tunneling

- A superconducting STM can tunnel Cooper pairs to the film:

$$\boxed{G = G_{2e} + G_{CP}}$$



(Naaman, Tyzer, Dynes, 2001).

More physical properties of the vortex metal

Cooper pair tunneling

- A superconducting STM can tunnel Cooper pairs to the film:

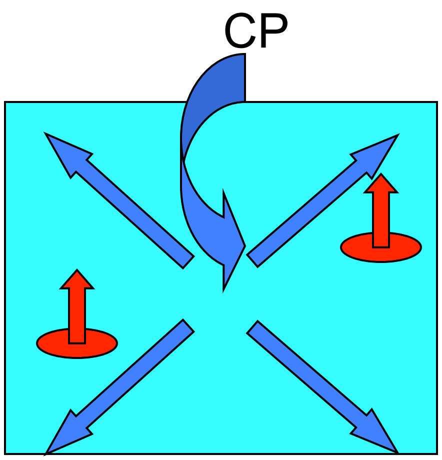
$$G = G_{2e} + G_{CP}$$

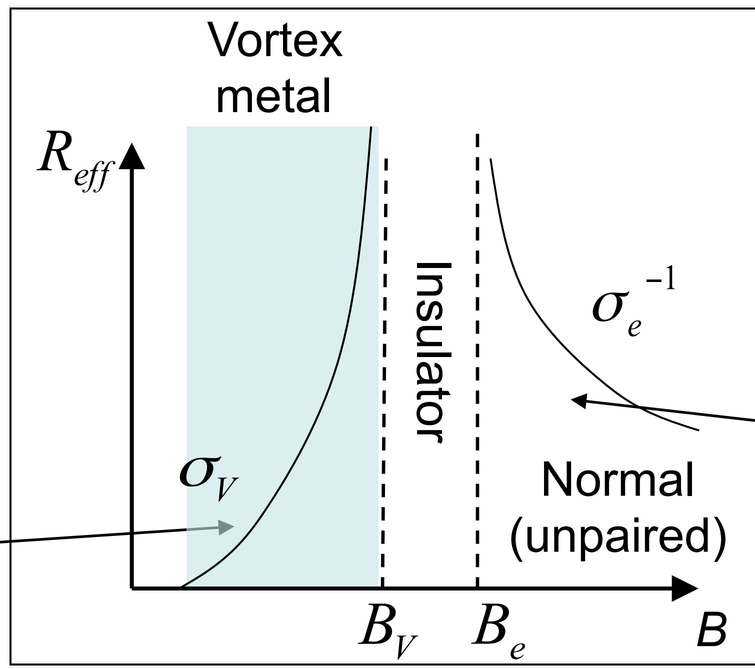
Vortex metal phase:

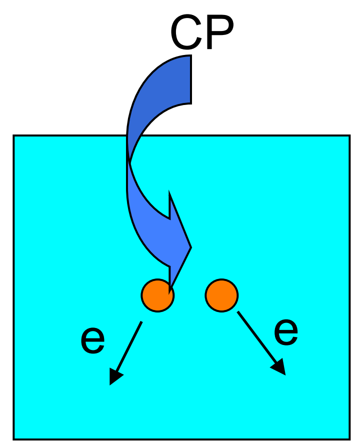
$$G_{CP} \sim \frac{1}{T^2} \exp(-\sigma_V \ln^2 T)$$

Normal phase:

$$G_{2e} \sim \sigma_e^{\ 2}$$







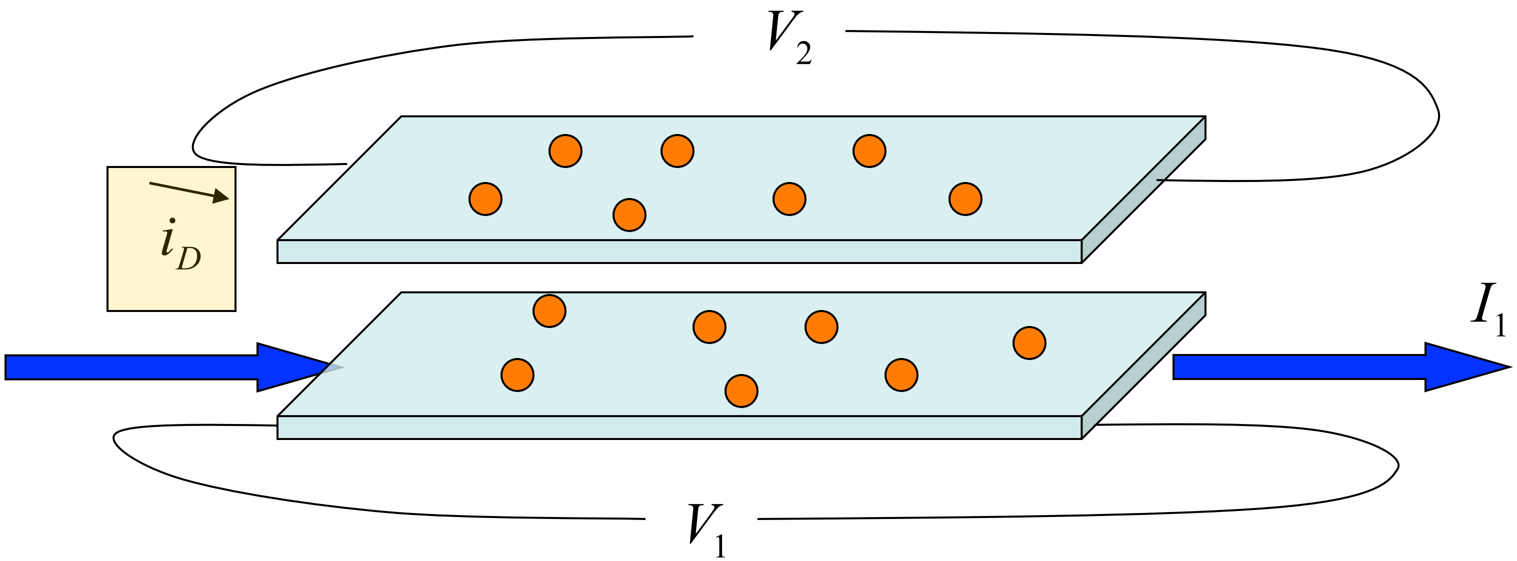
$G \approx G_{CP}$
strongly T dependent

$G \approx G_{2e}$
$\sim 1/\ln^2 T$

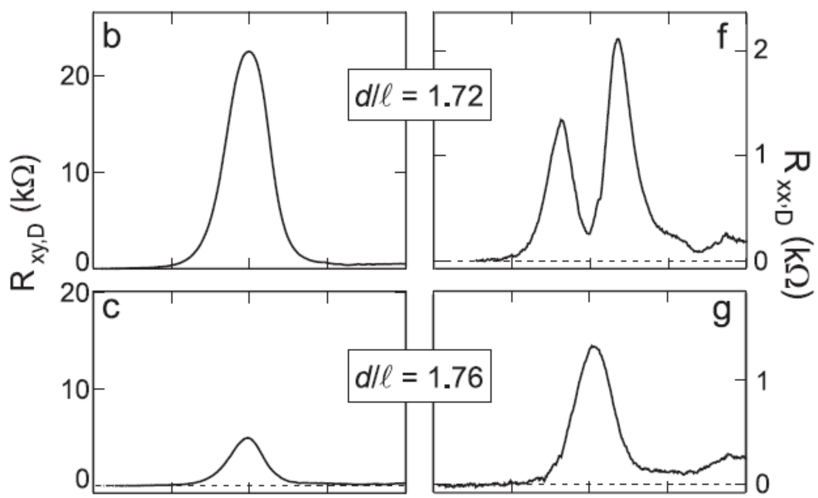
2DEG bilayers – Coulomb drag

Two thin electron gases:

$$R_D = \frac{V_2}{I_1}$$



Example: $\nu_T = 1$ "Excitonic condensate"



(Kellogg, Eisenstein, Pfeiffer, West, 2002)